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AN OVERVIEW OF FUNCTIONALIZED CELLULOSE-BASED ADSORBENTS FOR Cu(II) REMOVAL FROM AQUEOUS SYSTEMS

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Introduction

Copper contamination of aquatic environments is a significant environmental concern due to its toxicity to aquatic organisms and its widespread presence in industrial effluents from mining, metallurgy, electroplating, metal finishing, battery manufacturing and other industrial activities. Although copper is an essential trace element, excessive concentrations of Cu(II) in water can negatively affect ecosystems and water quality. Therefore, the development of efficient and environmentally friendly methods for Cu(II) removal is an important objective in wastewater treatment.

Adsorption is an attractive technology because of its operational simplicity, relatively low energy consumption and high potential for removing metal ions even at low concentrations. Cellulose is a promising starting material for adsorbents because it is abundant, renewable, biodegradable and rich in hydroxyl groups. However, pristine cellulose generally exhibits limited adsorption capacity toward Cu(II) due to the low accessibility and chemical reactivity of its native functional groups. To overcome this limitation, various surface functionalization strategies have been investigated to introduce carboxyl, amino, thiol and phosphate groups, which can enhance Cu(II) binding through ion exchange, electrostatic attraction, surface complexation and chelation.

Although numerous cellulose-based adsorbents have been developed for heavy-metal removal, the relationship between the type of functionalization, the resulting adsorption mechanism and Cu(II) retention performance remains an important aspect for practical wastewater treatment applications. The main goal of this study is to present and compare functionalization approaches described in the literature for improving Cu(II) retention by cellulose-based adsorbents, with particular emphasis on porous cellulose structures and cellulose-based sponges, and to correlate the introduced functional groups with the main mechanisms responsible for Cu(II) adsorption.

Materials and methods

Different strategies can be applied for the preparation of functionalized cellulose-based materials with enhanced affinity toward Cu(II):

Carboxylation/oxidation – introduces carboxyl groups (–COOH), which can become negatively charged ($–COO^-$) and enhance Cu(II) retention through ion exchange and surface complexation.

Amination – introduces amino groups ($–NH_2$) using reagents such as ethylenediamine or polyethyleneimine (PEI), providing electron-donating sites for Cu(II) coordination.

Thiolation/phosphorylation – introduces thiol (–SH) or phosphate groups ($–PO_3H_2$), which can form strong complexes with Cu(II).

Composite formation – combines cellulose with chitosan, alginate, silica, metal oxides, carbonaceous materials or magnetic nanoparticles to improve adsorption capacity, selectivity and stability.

These modifications can be applied to various cellulose architectures, including fibres, nanocellulose, hydrogels, aerogels, sponges, beads and membranes. Among them, cellulose-based sponges are particularly attractive for water treatment due to their interconnected porous structure, high water uptake, easy handling and potential for functionalization. Figure 1 presents a schematic representation of the main preparation steps for amine-functionalized cellulose-based sponges. The cellulose sponge is first modified with epichlorohydrin, followed by reaction with ethylenediamine to introduce amino groups onto the cellulose structure. These amino groups provide additional active sites with enhanced affinity toward Cu(II) ions, promoting their adsorption mainly through coordination interactions and resulting in an improved adsorption capacity.

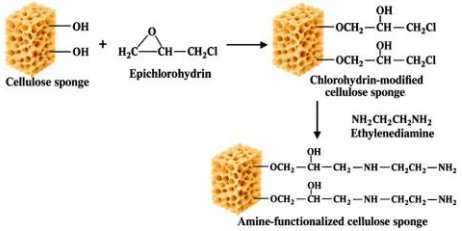


Figure 1 - Reaction scheme of the synthesis of the amine functionalized cellulose sponge.

Results and conclusions

Functionalization significantly improves the Cu(II) adsorption performance of cellulose-based materials. Amino and carboxyl groups provide stronger Cu(II)-binding sites than the native hydroxyl groups and porous sponge-like structures facilitate mass transfer, enable easy recovery and reuse of the adsorbent.

Despite promising laboratory results, further studies are needed under real wastewater conditions, considering competing ions, regeneration, metal recovery and scalability. Functionalized cellulose-based adsorbents, particularly sponges, offer a sustainable and versatile solution for Cu(II) removal from aqueous systems.